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COLLEGE OF AGRICULTURE
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SPARK ARRESTERS FOR MOTORIZED EQUIPMENT

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INTRODUCTION

THE INFLAMMABLE NATURE of vegetative ground cover during the dry summer season, throughout the major area of California, contributes to the fire hazards in fields and forests. In the rural districts, many fires have been attributed to ignition by the exhaust systems of motorized equipment. Fires started by internal-combustion engines may result from the emission of hot carbon particles in the exhaust stream; from contact between dry vegetation and hot exhaust pipes; or, under certain conditions, from actual contact between flames from the exhaust system and dry vegetation.

Carbon residue collects within the cylinder heads, in the mufflers, and on the piston heads of practically all internal-combustion engines. The amount and nature of this carbon depends somewhat upon the condition of the engine and upon the kind of fuel and lubricating oil used.

Under certain conditions, pieces of carbon residue break loose and are emitted with the exhaust gases. At the time of combustion, the gases within the engine cylinder range in temperature from 3000° to 4000° Fahrenheit; and they are exhausted at temperatures of 1200° to 1600° F. Since the temperature within the exhaust system is above the kindling point of the carbon, the carbon particles may well have temperatures approximating or even above exhaust temperatures, because they may be burning as they leave the engine. That they are hot enough to be incandescent is obvious when one watches a tractor, with no protective device on its exhaust system, working after dark. Sometimes a shower of sparks is thrown out in the exhaust stream when there is a sudden change in load or speed. Incandescent carbon particles may even be seen coming from the muffler tail-pipe of an automobile traveling the highway at night, and they often glow for several seconds after passing from the engine.

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The law, as passed by the 1931 California Legislature, regarding protective devices on internal-combustion engines, used under hazardous conditions, designates the following as a misdemeanor:

> Operating or causing to be operated any gas tractor, oil-burning engine, gas-propelled harvesting machine or autotruck in harvesting or moving grain or hay, or moving said tractor, engine, machine or autotruck in or near any grain or grass lands, unless he shall maintain attached to the exhaust on said gas tractor, oil-burning engine or gas-propelled harvesting machine an effective spark-arresting and burning carbon-arresting device.[4]

One question was raised immediately: What constitutes an effective spark-arresting device? The Divisions of Forestry and Agricultural Engineering, of the University of California, had made a few preliminary tests of spark arresters for tractors and harvesters in 1918.[5] On account of the development in recent years of new forms of arresters and of new types of tractors, the data on hand were not sufficient to give complete information on types of spark arresters fully complying with the law. In May, 1931, accordingly, the Stop Forest Fires Committee requested the Division of Agricultural Engineering to analyze the problem further. In addition, the Equipment Committee of the Rural Fire Institute of California, which had already selected this phase of fire prevention as an important problem, desired that additional study be made.

There was furthermore very little information available regarding the composition, size, and characteristics of the carbon particles emitted with the exhaust gases, or regarding the conditions under which fires might be started by carbon particles from internal-combustion engines or by contact with hot surfaces, such as exhaust pipes. The first step, accordingly, was to analyze some of this carbon material and to start fires in dry vegetation under different weather conditions, using carbon particles of various sizes and a section of exhaust pipe, both heated through the range of critical temperatures. The first part of this bulletin deals with this aspect of the problem, and the results of experiments with spark arresters are given in a later section.

CARBON COLLECTED FROM MOTORIZED EQUIPMENT

The amount of carbon ejected from an engine for a given length of time was not definitely determined. On one 60-hp. tractor of the U. S. Forest Service, however, 100 grams of carbon were caught during 100 hours of operation, or 1 gram per hour. The tractor had run a total of 3,900 hours.

[4] California Penal Code, No. 9. Sec. 384. Stats. 1931. Chap. 311, p. 749.

[5] Metcalf, Woodbridge. Fire protection for grain fields. California Agr. Exp. Sta. Bul. 295: 351–368. 1918. (Out of print.)

On a 40-hp. tractor of the U. S. Forest Service, 14.45 grams were caught in 144 hours of operation, or 0.1 gram per hour. This tractor had been run only 580 hours. These figures merely bear out the common observation that a worn engine produces more carbon than one in first-class condition.

Size of Carbon Particles.—Carbon was trapped by spark arresters on eight tractors, five used in general farm work, and three on road construction. The three latter were U. S. Forest Service tractors to which had been attached large spark traps of the inertia type with the final openings covered by 16-mesh-to-the-inch wire cloth.

TABLE 1

Screen Analysis of the Carbon Collected in Spark Arresters on Eight Tractors

Tyler screen	Size of opening, inches	Per cent retained
4-mesh	0.185	1.9
8-mesh	0.093	7.5
14-mesh	0.046	18.7
28-mesh	0.0232	27.5
Pan	....	44.4

The carbon collected from each tractor was screened through a set of standard Tyler square-mesh screens (table 1).

As the data (table 1) show, over half the carbon ejected by the tractors was coarser than the 28-mesh screen. In most samples the carbon particles were hard and granular, but in one case they were soft and flaky. Fifty-three such flakes were not screened because of their large sizes, ranging from ¼ to ¾-inch maximum diameter. One large flake, not included among these, measured 9/16 by 15/16 inches.

For the three tractors on which the time of operation was known, carbon was caught at rates ranging from 0.1 to 1.0 gram per hour. The rate of carbon accumulation should be considered in the design and use of spark arresters. A former tractor-service man reported a case of fires being started from one of his firm's tractors equipped with an arrester. Upon investigation, the chamber proved to be filled with carbon, which could be removed only by taking the arrester apart.

Kindling Temperature of Carbon.—A one-gram sample of each size of carbon caught from one tractor was analyzed to determine the quantity of ash and the kindling temperature (table 2).

The ash was not analyzed qualitatively except to determine that it

was mainly a form of iron, presumably worn from cylinders and rings.[6]

Since the kindling temperatures ranged from 887° to 1022° F,[7] it is evident that carbon can be ignited in the exhaust system of an internal-combustion engine.

Weight of Carbon Particles.—In weight, carbon particles from different samples varied widely. For example, 50 pieces from one sample passing through a 0.093-inch square mesh and caught on a 0.092-inch round-hole screen weighed 0.40 gram, or 0.008 gram each; while 100 pieces of another sample similarly screened weighed 0.11 gram, or 0.0011 gram each, a ratio of more than 7 to 1.

TABLE 2

KINDLING TEMPERATURE AND QUANTITY OF ASH FOR ONE-GRAM SAMPLES OF EACH SIZE OF CARBON

Tyler screen	Ash in grams	Kindling temperature of carbon retained, degrees Fahr.
4-mesh	0.810	....
8-mesh	0.813	1022
14-mesh	0.799	1022
28-mesh	0.761	1004
Pan	0.605	887

SELECTION OF CARBON FOR FIELD TRIALS

The carbon selected for the field tests must correspond in general type to that ejected by engines, must not break into smaller particles when handled, and must not coke in the furnace, later to be discharged as a wad rather than as separate particles. Furthermore, it must be available in quantity. Trials were made with the following forms of carbon: (1) carbon electrodes from dry cell batteries, (2) coal coke, (3) oil coke, (4) carbon scraped from pistons and cylinder heads of internal-combustion engines, and (5) cinders from coal-burning locomotives. Experiments comparing these carbons under controlled laboratory conditions are given in a later section.

No one of the carbons used represented all types ejected from internal-combustion engines. The battery carbon, being very hard and heavy, did not burn readily nor coke. It was considered a useful indicator of the ease with which different forms of vegetation are ignited under various weather conditions; and it represented an inert or nonflaming type of material.

[6] The analysis of carbon samples was made by H. W. Allinger, of the Division of Chemistry, University of California.

[7] All temperatures in this bulletin are in degrees Fahrenheit.

No field tests were made with coal coke. One form of oil coke was unsuitable because it coked readily. "Cokettes," an oil-coke product used in orchard heating, were extensively used.

Carbon scraped from engines was probably the most representative of material ejected by exhausts. It had a tendency to burn after leaving the furnace and to break down into smaller particles. In some cases there was some coking effect in the furnace.

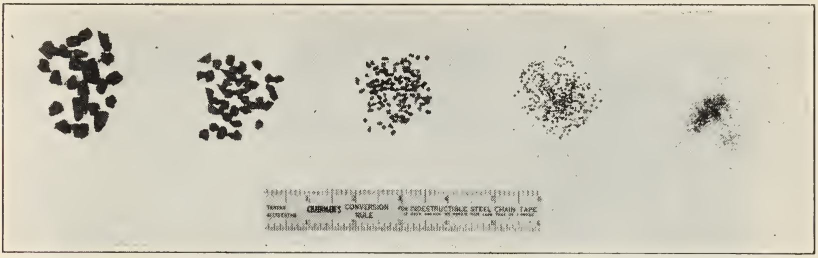

Fig. 1.—Comparative sizes of the five groups of carbon particles. Left to right, Nos. 1 to 5. Scale, in inches.

Cinders from coal-burning locomotives, collected on car roofs in Montana by members of the U. S. Forest Service, were used in a few field tests; but only small sizes were available. Being fairly inflammable, the coal cinders were not representative of the carbon ejected from internal-combustion engines.

TABLE 3

Screens Used in Selecting Carbon Samples

Carbon size No.	Passing through Tyler screen	Size of opening, inches	Retained on	Size of opening, inches
1	2-mesh	0.371	4-mesh hardware cloth	0.221
2	4-mesh	0.185	No. 11 round hole	0.170
3	8-mesh	0.093	No. 43 round hole	0.092
4	14-mesh	0.046	Tyler 28-mesh	0.023
5	28-mesh	0.023	Pan	0.000

Carbon particles caught in spark arresters on tractors were used in a few tests, but the procurable supply was limited.

Five classifications of carbon sizes (fig. 1) were used. The basis for segregation was a set of Tyler square-mesh screens in which the diameter of each succeeding opening was one-half that of the one preceding. The range of sizes within each group was kept to a minimum by inserting other screens with openings slightly smaller than those of the corresponding square-mesh screen (table 3). All screening was done by means of a Ro-Tap machine.

EXPERIMENTAL PROCEDURE AND TEST AREAS

Equipment for Spark Tests.—Equipment was devised for heating carbon to known temperatures and quickly ejecting it into vegetation, to determine the sizes and temperatures necessary to start fires.

A 2.5-kw. high-temperature, combustion tube furnace (fig. 2), rated at working temperatures up to 2500° F, was used for heating the carbon particles. Current was supplied by an engine-generator set mounted on a truck, and the temperature was controlled by voltage regulation.

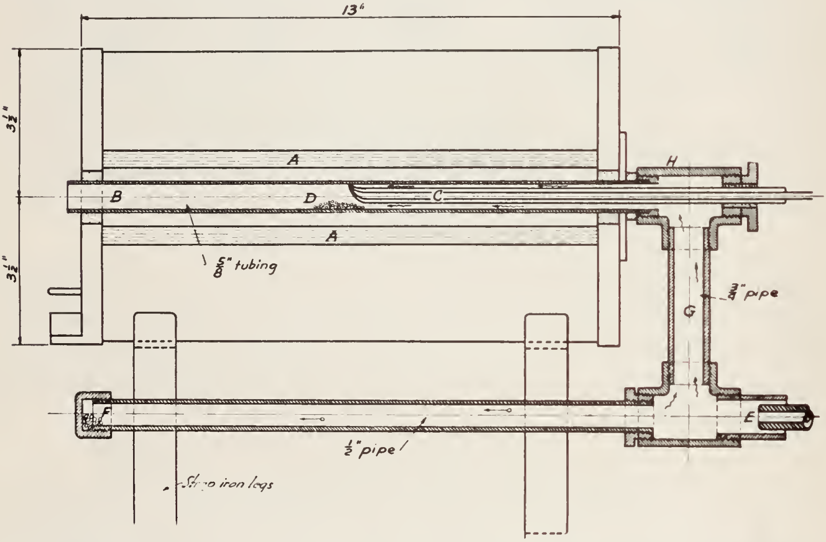

Fig. 2.—Portable electric tube furnace for heating carbon particles. *A*, Heating element; *B*, monel tube; *C*, thermocouple; *D*, carbon sample; *E*, rifle barrel; *F*, wads from cartridges; *G*, piping of the ejection system.

Within the tube the temperature was measured by a "platinum—platinum 10%—rhodium" thermocouple in a Fyrstan case, inserted in the combustion tube. This thermocouple was calibrated in millivolts, and the cold-junction was packed in a vacuum bottle containing ice. The sensitivity of the instrument was indicated by the fact that after the charge of carbon particles was placed in the furnace the millivolt meter needle would drop for a few seconds and then gradually return to the initial temperature.

Wind velocity was measured either with a standard Weather Bureau three-cup Tycos anemometer, mounted on a base so that the centers of the cups were 18 inches aboveground, or by a Biram-type 4-inch anemometer suspended 24 to 36 inches aboveground by a string from an arm on a staff and held into the wind by a light metal vane.

Air temperatures were read either from chemical thermometers suspended in the shade within 24 inches of the ground, or from the dry bulb of the psychrometer.

In measuring soil temperatures, a soil thermometer, standard grade, with pointed metal end, was inserted at such a depth that the bulb was at the surface of the soil.

Relative humidity was determined by sling or "egg-beater" types of psychrometers.

Fig. 3.—Dry oat grass (Davis).

Methods of Using the Equipment in the Field.—The truck carrying the 5-kw. engine-generator set was placed within 200 feet of the test plots, and the current was carried through 10-gauge weatherproof stranded conductors.

The furnace was placed on the ground in the plot, and the vegetation adjacent to it and to the instrument table, was cleared away. Fire guards around the plots, together with shovels, wet sacks, and knapsack pumps, were used to control the fires.

For each trial, two grams of carbon were used. The carbon particles burned but slightly when first put into the combustion tube, the flames ceasing within a few seconds, probably through deficiency of oxygen. Upon injection of the carbon, the millivolt meter needle dropped a few points. When it returned to the reading for the desired temperature, the carbon particles were ejected, either by shooting 0.22 or 0.32-caliber blank cartridges from guns, or by blowing into the pipe by mouth. The

carbon particles scattered widely, falling often within a few feet of the furnace but occasionally 25 to 30 feet away. In general, the shots were made with the wind. The results were considered negative unless the vegetation flamed. Smoke or a glow alone was not reported as a "fire." The number of spot fires resulting from a shot was not reported, although from one to eight spots may have ignited.

Field trials were conducted during the summers of 1931 and 1932 in short, dry, immature oat and barley stubble at Davis, in grasslands in

Fig. 4.—Barley stubble (Davis).

Tehama County, in brush fields near Mt. Shasta, and in pine needles near McCloud.

Dry Oats.—This field had been sown with oats that did not mature, because of a deficiency of moisture. The vegetative cover was mainly a mat of grasslike nature with small blades and stems up to 10 inches in length. There was a small percentage of barley, wild oats, and foxtail; but all were small plants (fig. 3).

Barley Stubble.—The barley field had been harvested with a combine, leaving the stubble 8 to 12 inches high. Blades, chaff, and some heads lay on the ground, clustered around the base of the stems (fig. 4).

Moisture samples of 200 to 300 grams each were taken. The average moisture content of twelve samples was 7.1 per cent, the range being from 2.2 to 14.5 per cent.

Range Grasses.—Field tests were made on two different plots of range grasses in Tehama County: one on the Owens ranch about 12 miles west

of Red Bluff, and the other on the Mohr ranch about 8 miles north of the same city.

Range land on the Owens ranch consisted of rolling hills covered with a heavy stand of fine, dry grass somewhat matted and trampled (fig. 5). The larger plants still standing were from 10 to 18 inches high. The species of grass identified were as follows: soft cheat *(Bromus hordeaceus)*, smooth flowered soft cheat *(Bromus racemosus)*, Mediterranean barley *(Hordeum gussoneanum)*, and wild oat *(Avena fatua)*. Other plants than grasses identified were: lupine *(Lupinus)*, filaree *(Erodium)*, fiddleneck *(Amsinckia)*, and blow wives *(Achyrachaena mollis)*.

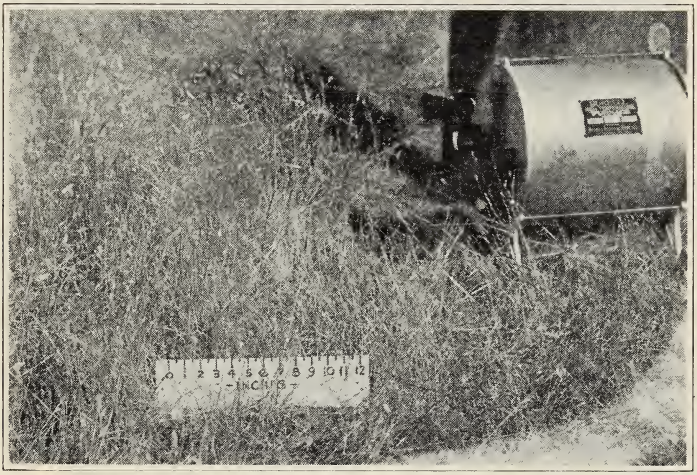

Fig. 5.—Dry grass on range land (Owens ranch, Tehama County).

The average moisture content for ten samples was 7.18 per cent, the range being from 3.1 to 20.2 per cent. The large variation in the moisture content was undoubtedly due to the relative proportion of the material in the sample from plants which were still in contact with their root system and those which had been broken from their root system and were lying on the surface of the ground. Although the two types of vegetation were apparently of the same degree of dryness, it became apparent in drying the samples that those which were still in their natural position with the roots and stems intact contained a much greater moisture content than those which had been broken off and were lying loosely on the ground. It is probable that ignition took place in most cases in the latter. This material in general, did not run higher than 3 per cent moisture.

On the Mohr ranch the range land consisted of a small flat along a

dry creek where the vegetation was a sparse stand of grass 4 to 5 inches high (fig. 6). The species of grass were identified as follows: soft cheat *(Bromus hordeaceus)*, few-flowered fescue *(Festuca reflexa)*, hairy-leaved fescue *(Festuca confusa)*, and red brome *(Bromus rubens)*. Other plants than grasses identified were as follows: Turkey mullein *(Eremocarpus setigerus)*, filaree *(Erodium)*, knotweed *(Polygonum californicum)*, and clover *(Trifolium microcephalum)*.

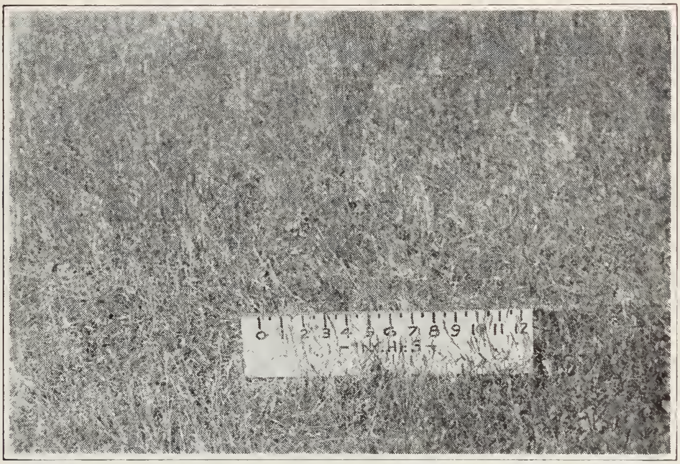

Fig. 6.—Dry vegetation (Mohr ranch, Tehama County).

The average moisture content of nine samples was 9.4 per cent, the range being from 2.9 to 20.7 per cent.

Pine Needles.—The test plot was located in a stand of second-growth ponderosa pine about fifty years old, near McCloud. The crown density, as expressed by foresters, was about 0.5, and the depth of needles on the ground averaged 2½ inches. There was no undergrowth or other ground cover (fig. 7).

The average moisture content of five samples was 7.1 per cent, the range being from 5.1 to 9.3 per cent.

Brush Field Litter.—This test plot was in a brush field near the town of Mt. Shasta. The vegetation consisted of manzanita, whitethorn ceanothus, and bracken (fig. 8). The litter on the ground, about an inch deep, was composed of twigs, branches, and leaves, typical of brush fields.

The average moisture content of three samples of the ground cover was 14.1 per cent, the range being from 11.5 to 17.7 per cent.

Weather Data.—The field tests were all made in August, when many range and forest fires are expected, but few grain fires, because the grain has been harvested.

During the 1931 field tests, the temperature readings ranged from 83° to 108°; the relative humidity, from 13 to 40 per cent; and the wind velocity, from 0 to 6 miles per hour (table 4).

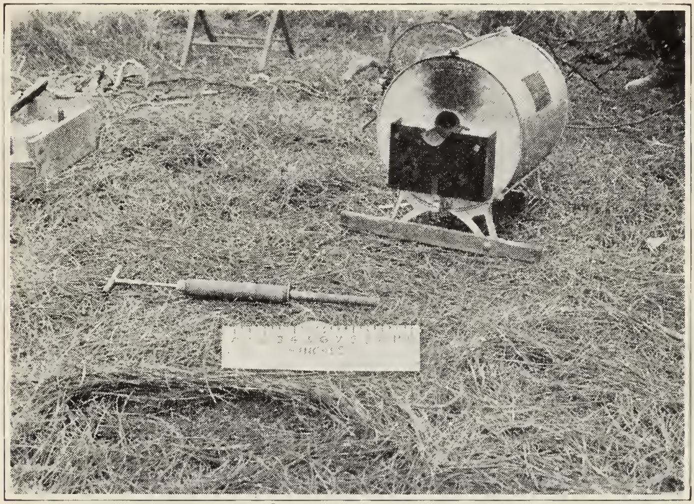

Fig. 7.—Pine needles (Shasta County).

Table 4 shows that, with the exception of one day, the 1932 tests were not made during a period of high fire hazard. The average temperatures were lower and the relative humidities higher than for the 1931 tests.

Fig. 8.—Brush field (Shasta County).

In general, at an air temperature of 80° the relative humidity was 30 per cent or less; at 100°, 20 per cent or less. At 110°, with a relative humidity of 10–12 per cent, the fire hazard was extremely high.

TABLE 4

CONDENSED WEATHER DATA, 1931 AND 1932

Place	Date	Time	Air temperature, degrees Fahr.		Relative humidity, per cent		Wind velocity, miles per hour	
			Range	Average	Range	Average	Range	Average
Davis	Aug. 21, 1931	3:05 p.m. to 5:34 p.m.	92 to 98	95	12 to 23	17	1.0 to 3.2	2.1
	Aug. 22, 1931	9:30 a.m. to 3:01 p.m.	83 to 101	94	19 to 30	21	0.0 to 6.0	5.0
	Aug. 25, 1931	12:45 p.m. to 4:46 p.m.	103 to 108	105	13 to 18	14	0.0 to 2.0	0.4
	Aug. 26, 1931	4:10 p.m. to 8:05 p.m.	75 to 101	87	14 to 40	28	....	....
Davis	Aug. 10, 1932	10:00 a.m. to 5:00 p.m.	73 to 84	80	30 to 43	35	1.0 to 5.0	3.9
	Aug. 11, 1932	10:00 a.m. to 4:30 p.m.	72 to 89	81	24 to 50	37	0.8 to 4.9	2.2
	Aug. 25, 1932	1:30 p.m. to 2:20 p.m.	100 to 103	101	19 to 22	20	4.5 to 6.0	5.3
Owens ranch	Aug. 16, 1932	10:00 a.m. to 5:30 p.m.	78 to 86	83	15 to 27	19	2.6 to 5.3	4.1
Mohr ranch	Aug. 17, 1932	9:30 a.m. to 4:45 p.m.	77 to 92	87	10 to 23	17	0.3 to 4.6	2.6
Mount Shasta	Aug. 18, 1932	1:00 p.m. to 5:45 p.m.	78 to 85	83	14 to 20	17	1.9 to 4.5	3.2
McCloud	Aug. 19, 1932	11:15 a.m. to 4:00 p.m.	78 to 84	81	16 to 29	20	0.3 to 1.9	1.3

Relation of Moisture Content of Vegetation to Time of Day.—Averages for the samples of vegetation consistently showed the lowest moisture content at between 1 and 3 p.m., the time of highest air temperature and lowest humidity. The average moisture content was 15 per cent above the mean at 11:00 a.m. and 5:30 p.m., and 30 per cent below the mean at 3:00 p.m., showing the rapid response of grass and pine needles to weather conditions.

Relation of Soil Temperatures to Air Temperatures.—Samples of vegetation brought into the laboratory and oven-dried required higher temperatures of sparks for ignition than in the field with equivalent air

TABLE 5

SOIL TEMPERATURES IN RELATION TO AIR TEMPERATURES

	Average air temperature, degrees Fahr.	Average soil temperature, degrees Fahr.	Difference, degrees Fahr.
Davis, barley stubble	83	101	18
Owens ranch, tall grass	83	101	18
Mohr ranch, short grass	87	110	23
Mt. Shasta, brush field	83	102	19
McCloud, pine needles	81	97	16

temperatures. A question was thus raised concerning the possible effect of higher temperatures on the vegetation lying on the ground in the fields exposed to sunshine. The temperature of the soil surface, measured with soil thermometers, ranged from 16° to 23° higher than the air temperature, a fact that may have affected the tendency to ignite. Evidently, therefore, ignition tests should be made in the field under natural conditions (table 5).

Effect of Humidity on Inflammability of Vegetation.—The effect of humidity cannot be segregated from that of temperature; but when the spark tests are grouped according to humidity, irrespective of temperature, the data show that at a humidity of 10 to 29 per cent, fires were started with No. 2 carbon at temperatures of 1300°; for 30 to 39 per cent, 1700°; and for 40 to 50 per cent, 1900°.

RESULTS OF SPARK TESTS IN THE FIELD

A summation of all the spark tests (table 6) includes the total number of shots made for each carbon size, the number of shots resulting in fires, and the number of carbon particles used for each shot in which a fire occurred. In this last case the number of pieces per gram, for the different sizes of cokettes, was taken as an average for all types of carbon used.

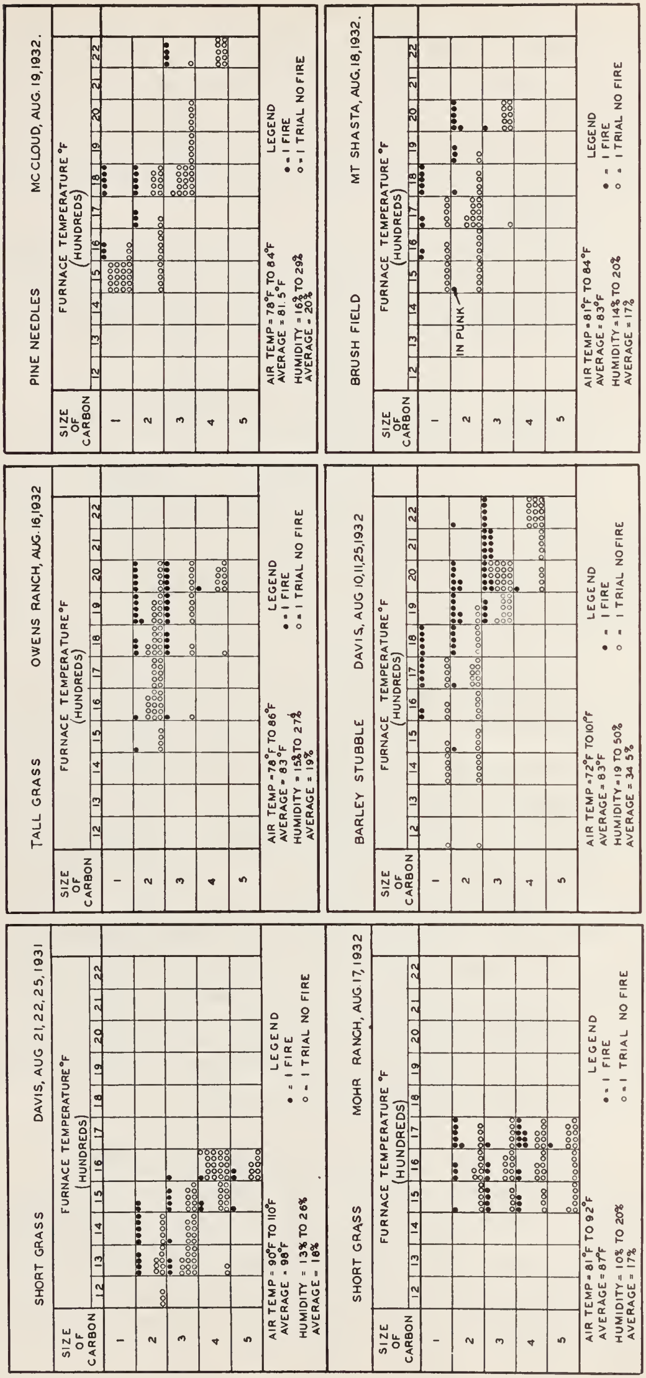

Fig. 9.—Results of certain aspects of the field trials, not shown in the tables.

The approximate ratio of the number, per fire, of carbon particles, sizes 2, 3, 4, and 5, was 2.5, 25, 100, and 5,000 to 1, respectively. Sizes 1 to 4, inclusive, appear, then, relatively hazardous; but the danger from size 5 may be small. In all four fires occurring with size 5, engine piston scrapings or railroad coal cinders were used.

TABLE 6

Summation of Spark Tests in Field

Carbon size No.	Number of shots	Number of fires	Number of pieces for each fire
1	100	30	40
2	245	77	102
3	192	61	983
4	148	19	4,050
5	27	4	210,000

All spark tests in the field are summarized in the graphs shown in figure 9. One field cannot be directly compared with another because of the numerous variables, including temperature, humidity, moisture content, and characteristics of the vegetation.

Spark Tests in Dry Grass.—In dry oats at Davis, 1931, fires were started with the carbon heated to temperatures of 1300° for sizes 2 and 3, and 1500° for sizes 4 and 5. In 1932, the range grasses on the Mohr ranch were ignited at temperatures of 1500° for sizes 2 to 4; and in one case ignition occurred with size 5 at a temperature of 1700°. On the Owens ranch a fire was started with size 2 at 1500°, and with size 3 at 1600°. Fires were not started consistently until the temperatures reached 1800°.

TABLE 7

Comparison of Temperature and Humidities, 1931 and 1932

Year	Place	Temperature, degrees Fahr.		Humidity, per cent	
		Range	Average	Range	Average
1931	Davis	90–110	98	13–26	18
1932	Mohr ranch	81– 92	87	10–20	17
1932	Owens ranch	78– 86	83	15–27	19

The plots on the Mohr and Owens ranches were most nearly comparable to the 1931 tests at Davis, as to the nature of the vegetation; but the temperatures required to start fires were about 200 degrees higher in 1932 than in 1931.

The air temperatures during the 1931 tests were higher than during the 1932 tests, but the average humidities were nearly the same (table 7).

Spark Tests in Brush Cover.—The vegetation on the ground in the brush fields was ignited at 1600° with size 1 carbon, at 1800° with size 2, and at 2000° with size 3, except that in one case dry rotten wood (punk) was ignited at 1500° with size 2, the same temperature and size that ignited grass on the Mohr and the Owens ranches.

Spark Tests in Pine Needle Litter.—Pine needles caught fire with size 1 carbon at 1600°, and at 1700° with size 2; but fires were not started with size 3 below 2200°.

These tests indicated that brush cover and pine needles (except in the case of punk) are about equally susceptible to carbon sparks but are less easily ignited than dry grass.

During tests in the brush field and the pine forest, several specimens of punk were placed near the carbon particles being ejected from the furnace. The punk was found not only to be readily ignited but to cause hang-over fires; that is, fires that did not blaze immediately, but continued to smoulder and finally burst into flame. In one case the elapsed time was 40 minutes.

With the other types of vegetation, the fires started within 1 to 3 seconds, except once when a brushfield fire was not observed until after 10 seconds.

Spark Tests in Barley Stubble.—Trials were made in barley stubble in 1932. The minimum temperature for ignition was 1500° with size 2 carbon. Fires were consistently started with sizes 1 and 2 at temperatures of 1700° and 1800°, and with size 3 at 1900°. With size 4 one fire started at 2000°, and one at 2400°.

Distance Fires Started by Sparks from Furnace.—The fires started at distances from 1 to 30 feet from the furnace, usually within 15 feet. No attempt was made to determine the maximum distance at which the sparks would start fires.

TESTS ON IGNITING VEGETATION BY MEANS OF HOT SURFACES

A possible cause of field fires is vegetation in contact with hot surfaces, as when the exhaust pipe of a truck passes through grass or grain. Vegetation sometimes lodges on an exhaust manifold when a tractor passes under trees or when straw falls or is blown against the engine of a combine.

A surface heater, devised to simulate a hot exhaust pipe, was used to determine at what temperatures vegetation might be ignited by hot sur-

faces. A 600-watt heating unit, like that used in a radiant heater, was mounted in a 5-inch length of seamless steel tubing, outside diameter 1¾ inches (fig. 10). To the ends of the tubing and perpendicular to its axis was attached a handle, which supported the wires conducting the electric current to the heating element, and also the thermocouple leads. A copper-constantan thermocouple was brazed to the surface of the tubing. The lead wires ran to the cold-junction, and were connected at will with the millivolt meter by means of a commutating switch.

Fig. 10.—Surface heater in use.

These tests were made in the same vegetation and during the same periods as the spark ignition experiments. The record includes the hour, air temperature, heater temperature, length of contact with vegetation (in seconds), relative humidity of the air, and result as to fire. In 35 out of 51 trials made, ignition occurred during periods of contact ranging from 0 to 120 seconds, with heater surface temperatures from 900° to 1282°. The air temperature range was from 65° to 100°; the relative humidity from 19 per cent to 44 per cent (table 8).

No fires started with temperatures of less than 800° for contacts of 2 minutes' duration. For temperatures above 800°, fires started 35 times out of 48 trials.

In general, the results are consistent; but a few are out of line with the trend, probably because of the element of chance involved in the variable vegetation. Fires started in one second or less after contact in 17 cases, showing the possibility of hot exhaust pipes' starting fires while the machine is moving.

Practically instantaneous ignition occurred in 5 out of 18 trials in the 1100° to 1199° temperature range, and in 14 out of 17 trials in the 1200° to 1299° range.

In the temperatures below 1100°, the shortest period of contact that started fire was 20 seconds—at a temperature of 1085°.

The lowest temperature at which fire started was 838°, with 2 minutes' contact; but with an increase of only 6° (844°), a fire started in 1 minute 10 seconds.

TABLE 8

SUMMARY OF FIRES STARTED BY CONTACT OF DRY OATS WITH A HOT SURFACE

Heater temperature, degrees Fahr.	Number of times fire resulted	Number of times no fire resulted
Less than 800	0	3
800 to 899	2	0
900 to 999	2	3
1000 to 1099	4	2
1100 to 1199	13	5
1200 to 1299	14	3
Total	35	16

No fires were started by contact with barley stubble at Davis, although the temperatures were as high as 1400°. Air temperature varied from 73° to 83°; relative humidity, from 20 to 50 per cent.

On the Owens ranch, fire started in grass on contact when the temperature of the pipe was 1390° (air temperature 86°, relative humidity 16 per cent). On the Mohr ranch, the pipe was covered with dry grass; and the temperature increased from 800° to 1225° before fire started (air temperature 90°, relative humidity 17 per cent).

Pine needles were not ignited by contact at 1400° but did start at 1340° when the pipe was covered with pine needles and the temperature was increased until ignition took place. Punk wood was ignited by contact at 1400° (air temperature 83°, relative humidity 16 per cent). The surface heater started fires when touched to vegetation at temperatures from 100° to 160° lower than the minimum temperatures at which carbon sparks started fires under the same conditions of vegetation and weather.

CONTROL EXPERIMENTS TO DETERMINE BURNING EFFECT OF CARBONS USED

Since the field trials indicated that the different sizes and kinds of carbon, when heated to the same temperature, varied in their tendency to start fires, it was desired to check these differences more accurately by means of laboratory tests. It was also desired to check the assumption

that the furnace temperatures used were within the range of temperatures imparted to carbon ejected by engines.

In these comparisons, the heated carbon particles were ejected upon sheets of cotton (outing) flannel, and the resulting scorched or burned spots were observed.

In comparing the different types of carbon, 12 × 12 inch sheets of the cotton flannel were placed in a pan 28 inches from the high-temperature combustion furnace used in the field trials. A one-gram sample of the carbon under test was heated in the furnace to the desired temperature and ejected upon the cloth by blowing through the furnace tube. Two trials were made with each size and type of carbon at intervals of 100°. The cloths could be readily segregated as to comparative degrees of scorching.

TABLE 9

TEMPERATURES PRODUCING MODERATE SCORCH

Type of carbon	Carbon size	Temperatures producing moderate scorch, degrees Fahr.
Battery	2	1100
Cokette	2	1100
Engine scrapings	2	1100
Battery and cokette	3	1300
Engine scrapings	3	1100
Battery and cokette	4	1700
Engine scrapings	4	1100

For comparing the effects of the different carbon temperatures, the results were classified into four degrees of scorch:

1. None; no scorched spots visible.
2. Slight; faintly visible scorched spots.
3. Moderate; distinct brown or black scorched spots, but no holes burned through the cloth.
4. Heavy; very distinct black spots, and some holes burned through the cloth.

Battery carbon and cokettes gave practically the same results for the three sizes used, namely 2, 3, and 4. For size 2, engine scrapings, battery carbon, and cokettes gave approximately equal scorch at temperatures from 900° (slight scorch) to 1200° (heavy scorch). For size 3, engine scrapings caused equivalent scorch at temperatures of 100° to 200° lower than did battery carbon and cokettes. For size 4, engine scrapings caused equivalent scorch at temperatures of 300° to 600° lower than did

battery carbon and cokettes (table 9). Some size 4 carbon removed from tractor spark arresters caused equivalent scorch at temperatures of 300° to 500° lower than battery carbon and cokettes.

Table 9 shows that moderate scorch was caused by scrapings of sizes 2, 3, and 4 at 1100°, irrespective of size; while for battery carbon and cokettes the same effect was produced by size 2 at 1100°, by size 3 at 1300°, and size 4 at 1700°.

Heavy scorch was caused by size 2 of battery carbon, cokette, and engine scrapings at 1200°; by size 3 of engine scrapings at 1300°; and of battery carbon and cokette at 1400°. With size 4, it was not obtained by battery carbon and cokettes until a temperature of 1800° was reached, but occurred at 1500° for engine scrapings.

These tests were intended to correlate the probability of fires' being started by the different sizes and temperatures of carbon discharged from an engine exhaust, with the results of field trials where battery carbon or cokettes were mainly used. An approximate correlation between cokettes and engine scrapings follows:

Cokettes size 2 at 1100°=engine scrapings size 2 at 1100°
Cokettes size 3 at 1350°=engine scrapings size 3 at 1200°
Cokettes size 4 at 1750°=engine scrapings size 4 at 1333°

Carbon particles designated as size 5 are those that pass through a 28-mesh screen with openings 0.023 inch in diameter; for cokettes this means about 15,000 pieces per gram. Although this extremely small size would not appear to be a fire hazard, three fires were started in grass with such piston scrapings and railroad carbon within a few feet of the furnace. In special trials of the scorching effect of size 5, made with cotton flannel sheets, the cokettes caused no scorch up to 1500° and moderate scorch at 1600°. The engine scrapings, however, caused slight scorch at 1200° and moderate scorch at 1500°. They glowed brightly when ejected at 1200°, appearing to burn as they traveled through the air. When the furnace was raised to a height of 5 feet, they ceased to glow slightly less than 9 feet from the furnace, while falling through the air. At 1500° they caused moderate scorch on the cloth 7 feet from the furnace.

These tests and the field trials indicated that fires may be started by size 5 carbon striking dry grass within a few feet of the exhaust; but if the exhaust pipe is vertical the carbon particles will be cooled below the danger point before reaching the ground.

Of the other sizes of carbon, some particles were still glowing when they fell 20 to 60 feet from the furnace. During field tests at night, carbon of miscellaneous sizes that had been caught in a spark arrester

glowed from 9 to 30 seconds after leaving the furnace. Scrapings of size 4 glowed from 10 to 15 seconds. According to these results, cooling by passing a short distance through the air does not always prevent fires from particles of size 4 and larger.

Comparison of Carbon Used in the Field Tests with Carbon Ejected by Engines.—A tractor, with the arrester removed, was run under full load on a Sprague electric belt dynamometer. Battery carbon and cokettes of size 3 were fed into the carburetor air intake. The particles were discharged from the exhaust to a large sheet of cotton flannel on the ground, causing scorched spots equivalent to those obtained from size 3 battery carbons and cokettes from the furnace at 1300°. Some of the spots were 8 feet from the exhaust pipe.

Most of the carbon particles were ejected almost instantaneously, some within ten seconds after being fed into the carburetor, whereas with the furnace a half minute or more was required to bring the size 3 particles up to the furnace temperature. According to this test, non-flaming particles may have a temperature of at least 1300°, or higher in case they are not discharged soon after becoming dislodged from the piston head or cylinder head.

A Model A Ford engine, run for 24,000 miles without removal of the carbon, was treated with a carbon remover one evening. The next morning the engine was run slowly to warm up, then "raced." Particles of carbon ejected from the engine ignited cotton batting held in a frame 18 inches back of the tail pipe, even after passing through the regular muffler and exhaust-pipe system.

The same effect was obtained by discharging size 4 engine scrapings from the electric furnace at 1400° upon the same sample of cotton batting held 3 feet away.

These trials indicate that the temperatures used in the field trials with the furnace were within the range of engine exhaust systems—a conclusion further substantiated by a review of literature on internal-combustion engine temperatures. Ricardo[8] gives 1640° as the temperature of the exhaust gas at the completion of the cycle. General Motors Research Laboratories[9] report the maximum temperature of exhaust gases of automobile engines as 1000° to 1600°.

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[8] Ricardo, Harry R. The high speed internal-combustion engine. 435 p. 292 fig. Blackie and Son, London. 1931.

[9] Correspondence with Ernest E. Wilson. Dynamics Section General Motors Research Laboratory, June 4, 1931.

EXPERIMENTAL PROCEDURE IN TESTING SPARK ARRESTERS

Many spark arresters in common use, and some experimental arresters, were tested first as to their efficiency in arresting carbon particles, and second as to their restrictive effect upon the engine exhaust system. Tests were made on these arresters while attached to the exhaust system of a 28-hp. 4-cylinder engine having a 4⅛-inch bore and a 5¼-inch stroke and operating at 1,150 r.p.m. Being belted to a Sprague dynamometer, the engine could be run under load as well as idling.

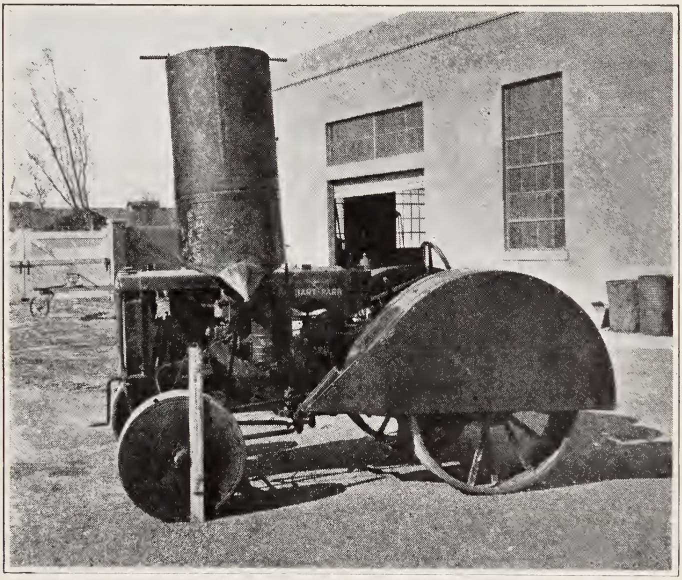

Fig. 11.—Tractor with spark trap in which the arrester efficiency tests were made.

Two sets of tests were run on each arrester. In the first, which were of a visible nature, 2-gram samples of carbon particles, sizes 2, 3, 4, and 5 (table 3), were heated to incandescence in a small combustion-tube furnace (fig. 2) and then introduced into the exhaust system through the throat of a Venturi tube built into the exhaust line, between the manifold and arrester. Because of the low pressure in the throat of the Venturi tube, carbon particles could be introduced against the back pressure of the exhaust system. These tests were run at night so that the path taken by any carbon particles passing through the arrester, together with characteristics peculiar to any one arrester, could be observed.

The actual efficiencies of the arresters were determined in a second series of tests, more positive in nature. The arrester, while attached to

the same engine, was entirely enclosed in a 24 × 36 inch trap (fig. 11) made of 20-gauge iron, with a hoppered bottom having, at the lowest point, an outlet for carbon removal. The top of the trap, telescoping the bottom part, was easily removed, making the arrester readily accessible. The exhaust gases escaped through a screened opening, 8 inches in diameter, located in the top.

Three tests, in which 100-gram samples of carbon sizes 2, 3, and 4 were used, were run on each arrester while the engine was working under full load. Idling and variable speed tests were run only on the arresters that showed high efficiencies while tested under load.

At this point it was thought unnecessary to include carbon particles of size 5 in the test. Field trials had shown that carbon of this size was not apt to start fires but, instead, lost its heat rapidly. When heated to an initial temperature of 1800°, it ceased to glow within a distance of 9 feet from the furnace. In practice, therefore, the exhaust pipe could be turned up to discharge into the air, thus providing the necessary distance for cooling the smaller particles before they reached the ground.

All carbon samples used in this test were oven-dried because the moisture content of the sample affected the final results. In other words, the temperature of the exhaust gas was sufficiently high to drive off this moisture, which, in some cases, amounted to as much as 6 per cent by weight.

After each test, the carbon was removed from the arrester and trap and was screened to determine how much it had been broken up. For example, the total weight of carbon passing through one arrester and caught in the trap was 23.99 grams. Of this amount, as shown by the screen analysis, 17.43 grams was of the same size as the original sample, while the difference of 6.56 grams was broken up finer than the original sample. In computing the efficiency of this arrester for carbon particles of this particle size, the 6.56 grams was not charged against the arrester.

A comparison of the screen analyses showed little variation in the extent to which the different arresters broke up the carbon. Probably the small variation noted resulted from differences in the carbon samples. As nearly as possible, however, the same carbon material was used throughout all tests.

Though carbon samples of 100 grams each were employed for each test, the efficiencies were based upon the total carbon caught in both the arrester and the trap. Occasionally some carbon fed into the line was drawn back into the exhaust manifold at the completion of a run, with those arresters that retained the carbon in the exhaust line until it became fine enough to pass through the arrester. Since occasionally some

of the carbon drawn back into the manifold would reappear in the next run, the total caught amounted to 100 grams plus or minus a small amount.

Only the carbon that retained its original size after passing through the arrester was considered in determining the efficiency for any one size. For example, the average of the total carbon caught in the test on one arrester was 100.40 grams. The average screen analysis after the tests showed the weight of original carbon in the trap to be 17.43 grams. The efficiency of this arrester for carbon size 2 was then found in the following manner:

$$\text{Efficiency} = \frac{100.40-17.43}{100.40} \times 100 = 82.64 \text{ per cent.}$$

The efficiency of the arrester for each size of carbon was determined in the same manner.

Sometimes the arrester did not retain the carbon particles yet broke them up somewhat; so it was credited with the amount that it reduced their size. For example, the average weight of carbon size 4 for the one arrester was zero; yet the efficiency, for this size, was rated at 15.36 per cent because this amount of carbon had been reduced in size. In this instance the efficiency $= \dfrac{98.26-83.17}{98.26} \times 100 = 15.36$ per cent. Another interesting case was that of an experimental harvester arrester which received an efficiency rating of 100 per cent for carbon particle size 3 although an average of 3.71 grams passed through it. All the carbon of this size passing the arrester, however, became smaller than the original.

When practicable, the restrictive effect of the different arresters was measured by a U-tube manometer containing water and having one side attached to the exhaust pipe just ahead of the arrester, while the other side was open to the air. In a few instances the water had to be replaced with mercury to measure higher pressures.

TESTS OF INERTIA-TYPE ARRESTERS

The Yuba Spark Arrester.—The original Yuba arrester used in this experiment (fig. 12) consisted of an inner cylinder cast integral with the base, an outer cylinder concentric with the inner and made of 18-gauge steel, a top cast in the shape of a semicircle of revolution, and a cast-iron spiral held by a pin in the central cylinder. The spiral was located with its top 1½ inches below the top of the inner cylinder. Three lips cast as a part of the top and bottom provided a place for attaching three bolts, which held the arrester together.

As the gas and carbon particles passed through the spiral, they were set into a swirling motion. Upon leaving the inner cylinder, the gas passed through the opening in the top directly to the outside, while the

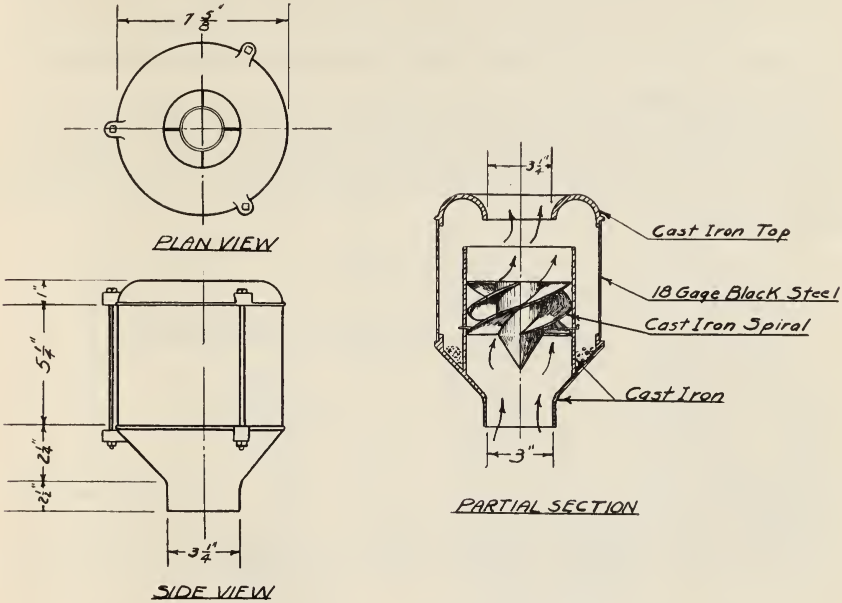

Fig. 12.—Yuba spark arrester (original).

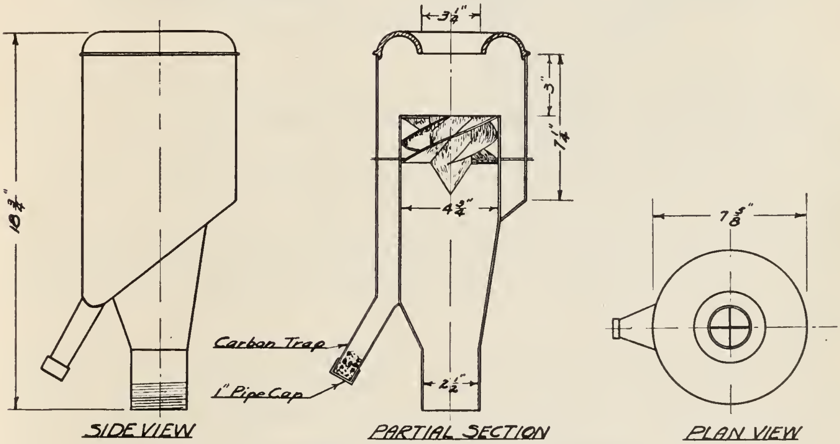

Fig. 13.—Yuba spark arrester (modified).

carbon particles were thrown by centrifugal force into the chamber between the inner and outer cylinders, where they were retained.

Tests conducted after dark, with glowing carbon particles, showed pieces of carbon occasionally leaving the spiral and hitting the inside wall of the inner cylinder at such an angle that they would bounce back

into the exhaust stream and be carried out through the opening in the top. By a slight modification, in which the spiral was raised until its top was flush with the top of the inner cylinder, and by means of a new outer shell 2 inches longer than the original (fig. 12), this fault was nearly eliminated. The new shell was also made with a hoppered bottom to facilitate cleaning.

The modified arrester (fig. 13) offered very little restriction on the exhaust system, the gas passing almost directly through it. When attached to the test engine, it caused a back pressure of 1.75 inches of water (table 10).

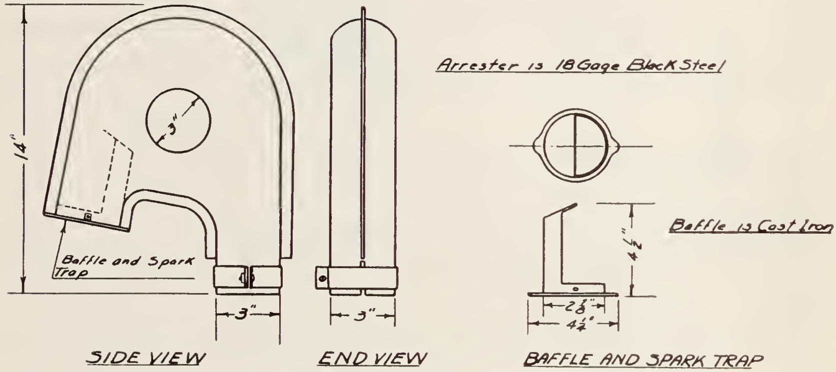

Fig. 14.—Cletrac cyclone spark arrester.

The efficiencies for this arrester, in its original form, were 98.0, 96.8, and 69.3 per cent, respectively, for carbon particle sizes 2, 3, and 4. In the modified design these efficiencies were raised to 99.6, 99.3, and 97.6 per cent for the three respective sizes of carbon particles (table 11). The efficiency of the rebuilt arrester was from 1.3 per cent to 3.2 per cent lower when tested in a horizontal position than when tested in a vertical position (table 11). The factory now builds this improved model.

The Cletrac Cyclone Arrester.—The spark arrester known as the cyclone, goose-neck, or question mark, consists of an outer shell, stamped in two parts from 18-gauge steel, then clinched together and held by a seam completely encircling it (fig. 14). Three-inch openings through the center of each side permit the exhaust gas to pass outside. A spark trap located in the path of the gas collects and retains the carbon particles.

Upon entering the arrester, the gas and carbon particles are immediately directed through a circular course. The centrifugal force thus set up throws the particles to the outer edge of the exhaust stream, where

they are separated from the gas by the baffle and fall into the trap. The trap may be removed for cleaning by taking out one bolt.

After a complete series of tests with the arrester in its original form, the outlets were covered with iron-wire screen of 16 meshes per inch, and another complete series was run.

The efficiencies for the Cletrac Cyclone were 98.7, 98.2, and 79.0 per cent, respectively, for carbon sizes 2, 3, and 4 without screens; 100, 99.9, and 80.8 per cent, respectively, when the outlets were screened (table 11).

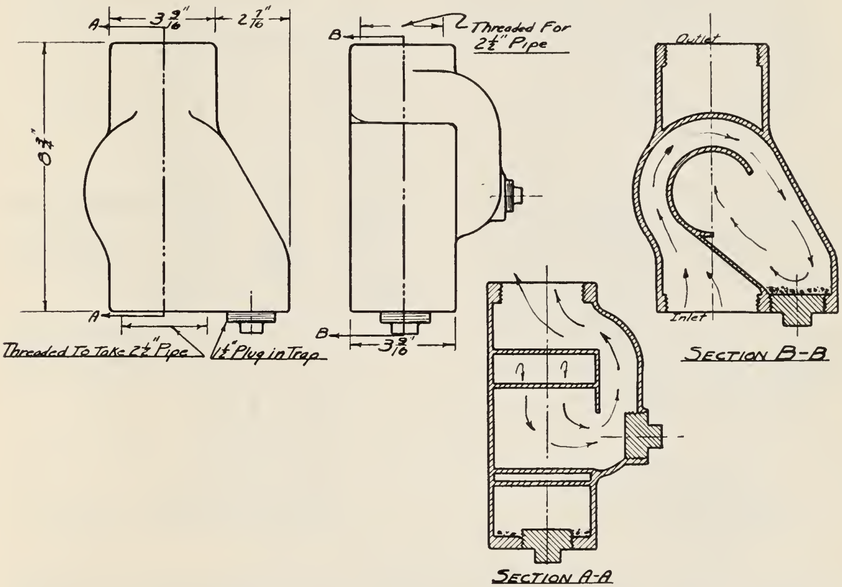

Fig 15.—Caterpillar spark arrester.

The back pressure was 4.75 inches of water for the arrester without screens and 5.75 inches when the screens were applied (table 10).

The Caterpillar Spark Arrester.—This arrester consists of a one-piece iron casting (fig. 15). It works on the same principle as the cyclone, except that the exhaust gas is carried through an additional 270° and discharged in line with the entrance after the carbon particles have been separated from the gas stream. The arrester, therefore, can be located close to the manifold; and a tail pipe can carry the gas away. No beneficial results, as far as separating the carbon is concerned, are gained in turning the exhaust gas through the last 270°.

The efficiencies were 94.0, 93.3, and 77.0 per cent, respectively, for carbon sizes 2, 3, and 4 (table 11). The back pressure amounted to 12.15 inches of water (table 10).

A field study of this arrester showed that very little carbon was ever retained in the trap. The reason might possibly have been the nearness, in some cases, of the arrester to the exhaust manifold, resulting in temperatures high enough to ignite the carbon. The most likely explanation, however, is that the space provided for collecting the carbon is too small; after a small amount of carbon accumulates, the rest is gradually carried out in the exhaust stream.

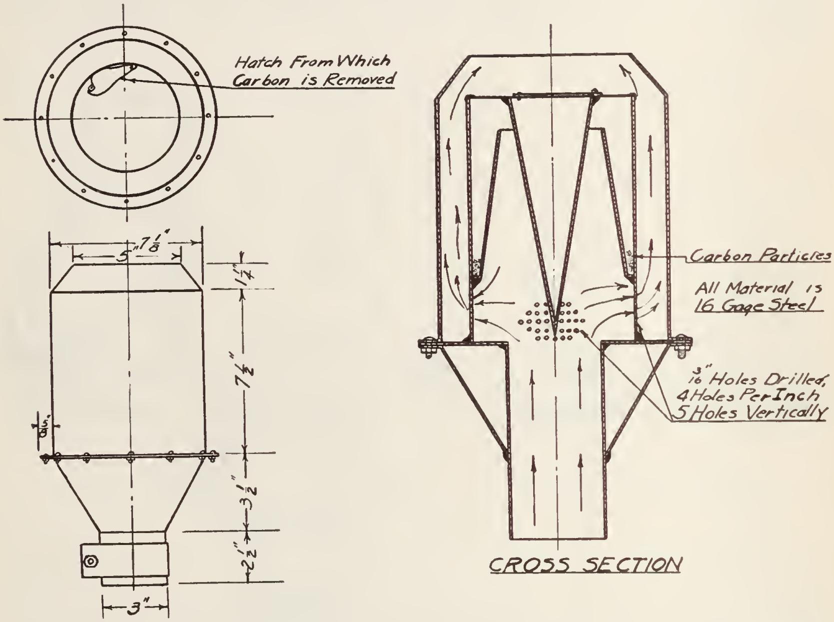

Fig. 16.—Funke experimental spark arrester. (Cross section drawn on one-half larger scale.)

The Funke Spark Arrester.—An experimental arrester (fig. 16) designed and built by F. W. Funke, Senior Forest Ranger, U. S. Forest Service, showed considerable promise. An outer cylinder is enclosed at the lower end and tapered to a 5-inch outlet at the top; and an inner cylinder, concentric with it, is enclosed at the top and opens at the bottom directly into the exhaust pipe. A series of $\frac{3}{16}$-inch holes, four per inch horizontally and five vertically, near the base of the inner cylinder, permit the gas to flow into the outer cylinder and thence to the outside. A cone centered and attached, inverted, to the top of the inner cylinder splits the stream of carbon particles, directing them through an opening made between it and the walls of the frustum of another cone. The latter frustum is open at both ends, with the larger end attached to the inside wall of the inner cylinder 2 inches from its base. The two cones

taper toward each other, providing at their closest point an opening of ½ inch (fig. 16).

Upon entering the arrester, the carbon particles, because of their inertia, continue in a straight line until deflected by the inverted cone, while the gas turns more or less abruptly, flowing through the holes in the side of the inner cylinder. Having passed the narrow opening between the two cones, the carbon particles fall into a space formed by the

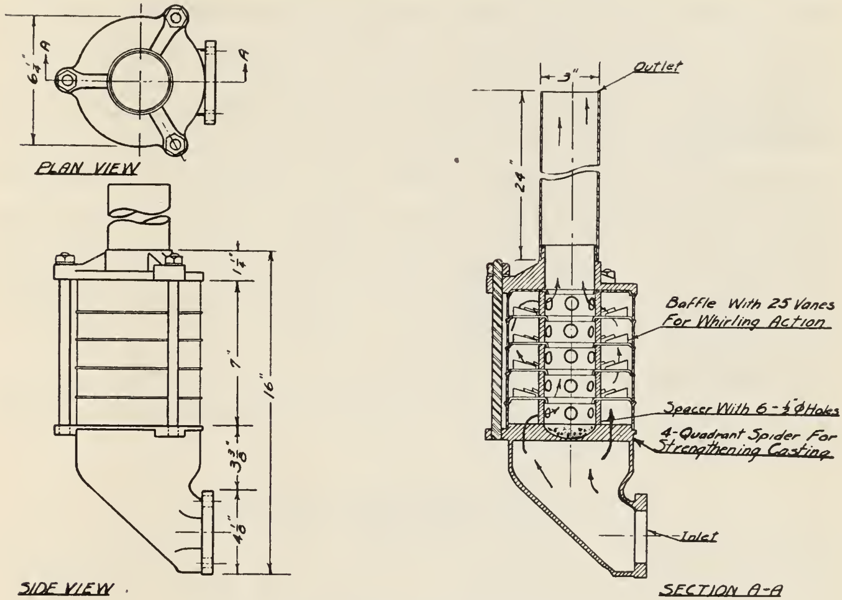

Fig. 17.—John Deere spark arrester.

outside wall of the frustum of the cone and the inside wall of the inner cylinder, in the top of which an opening with a removable covering permits one to clean the entrapped carbon from the arrester.

The efficiencies were 99.9, 96.0, and 94.3 per cent, respectively, for carbon sizes 2, 3, and 4 (table 11). The back pressure amounted to 2.75 inches of water (table 10).

The John Deere Spark Arrester.—Though not in the inertia group, the John Deere arrester does resemble inertia types, in that the gas is set into a swirling motion by the use of vane-type baffles between the different sections.

This arrester (fig. 17) is made up of similar sections superimposed, each consisting of a central spacer with six holes equally spaced around the periphery to permit passage of the gas between the outer and inner chambers, and with an outer shell. A baffle, with twenty-five vanes which impart a swirling motion to the gas, forms the top of each section, be-

tween the central spacer and the outer shell. The arrester consists of five such sections, each slightly telescoped together, held between two castings. The bottom casting is so shaped that it can be connected to the exhaust manifold, while the top one provides a connection for a tail pipe to carry the gas away from the engine.

The lower end of the inner cylinder, formed by the five spacers, is tight, so that the gas passes through the holes in the spacer, between the outer and inner chambers. After reaching the first section, the gas has two possible paths: it may pass immediately through the holes in the first spacer into the inner chamber, whence it is free to go into the open; or it may travel vertically from one section to the next, passing through the baffles between each section until the last is reached, and then leaving the arrester through the inner chamber. The gas is set into a swirling motion by the baffles as it goes from one section to the next. Some carbon remained in the lower end of the inner cylinder at the end of a test, but much passed out of the arrester with the exhaust gas, as the tests indicated. Obviously, in the design of this arrester, no place is provided for the retention of carbon material.

The efficiencies were 17.6, 17.9, and 11.8 per cent for carbon sizes 2, 3, and 4, respectively (table 11). The back pressure amounted to 4.25 inches of water (table 10).

TESTS OF SCREEN-TYPE ARRESTERS

The McCormick-Deering Spark Arrester.—This device (fig. 18) is so constructed that the exhaust gases must pass through two thicknesses of 10-mesh, No. 20 iron-wire screen, twice before they are discharged. Any carbon material smaller in diameter than the size of screen opening passes through the arrester with the gas. The coarser carbon material remains in the exhaust line, pounding about till its size has been reduced sufficiently to pass the screen.

The openings in the two layers of screen do not always coincide; and, since they are rather loosely held together, carbon particles are sometimes caught and held between the screen walls, especially near the point. Any large amount retained by the screen increased the restrictive effect of the arrester. For example, when a 100-gram sample of size 2 carbon was gradually introduced into the line, the back pressure increased from 10.5 inches of water at the beginning of the test to 76.07 at the end, while the pulley speed dropped 20 revolutions per minute. On the other hand, when a test was run with No. 4 carbon, the back pressure increased only 2.1 inches of water (table 10). In the latter case, most of the carbon was small enough to pass through the screen, and the speed did not fluctuate to any great extent.

Sometimes, under operating conditions, the carbon caught and held between the screen layers and inside the cone tip may catch fire because of the high temperatures of the exhaust gas. Thus the lower tip may burn off, decreasing the efficiency of the arrester. This tendency was reported in one case.

The efficiency was 100, 99.9, and 18.5 per cent, respectively, for carbon sizes 2, 3, and 4 (table 11).

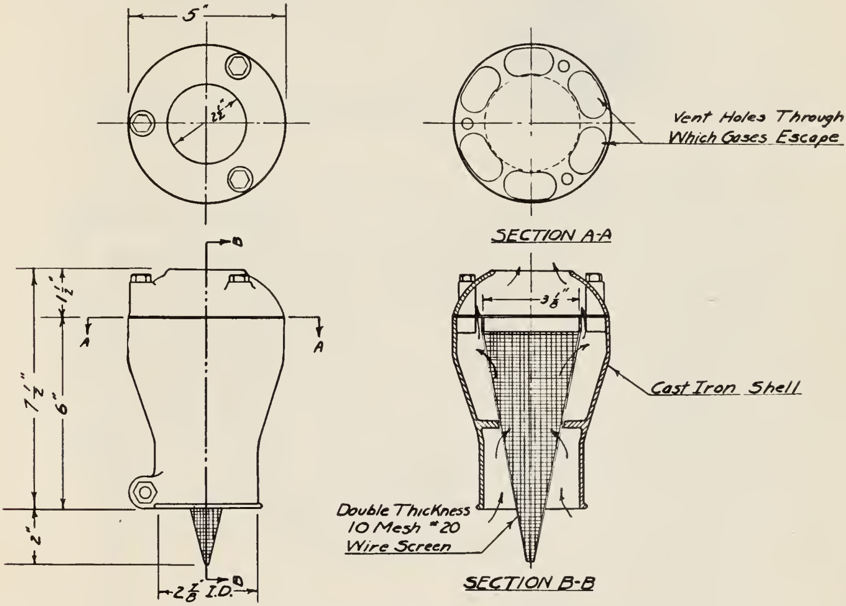

Fig. 18.—McCormick-Deering spark arrester.

Experimental Spark Arrester.—An experimental device of the screen type was built up primarily to test screens of different composition for resistance to heat and vibration. It consisted of a pipe, 4 inches in diameter and 30 inches long, made of 18-gauge black steel (fig. 19). The upper end was closed off; and three rows, each including nine 1-inch holes, were drilled around its circumference. The first row was 1 inch below the top of the pipe; and the next two rows were 3 inches and 5 inches, respectively, below the top. A shell of the same weight steel, 8 inches in diameter and 9 inches long, was placed concentric with the upper end of the pipe. This shell was closed around the pipe 2 inches below the bottom row of holes. Its top extended 2 inches above the end of the center pipe and had an opening 5 inches in diameter, covered with 16-mesh, No. 1 Nichrome wire screen. The size of the wire in the screen was 0.019 inch, which gave a net opening of 48 per cent of the total area. The screen had a total area of 19.6 square inches, with a net

opening of 9.4 square inches. It was held in place by an annular plate bolted to the top of the shell.

The efficiency of this arrester was 100, 100, and 71 per cent for carbon

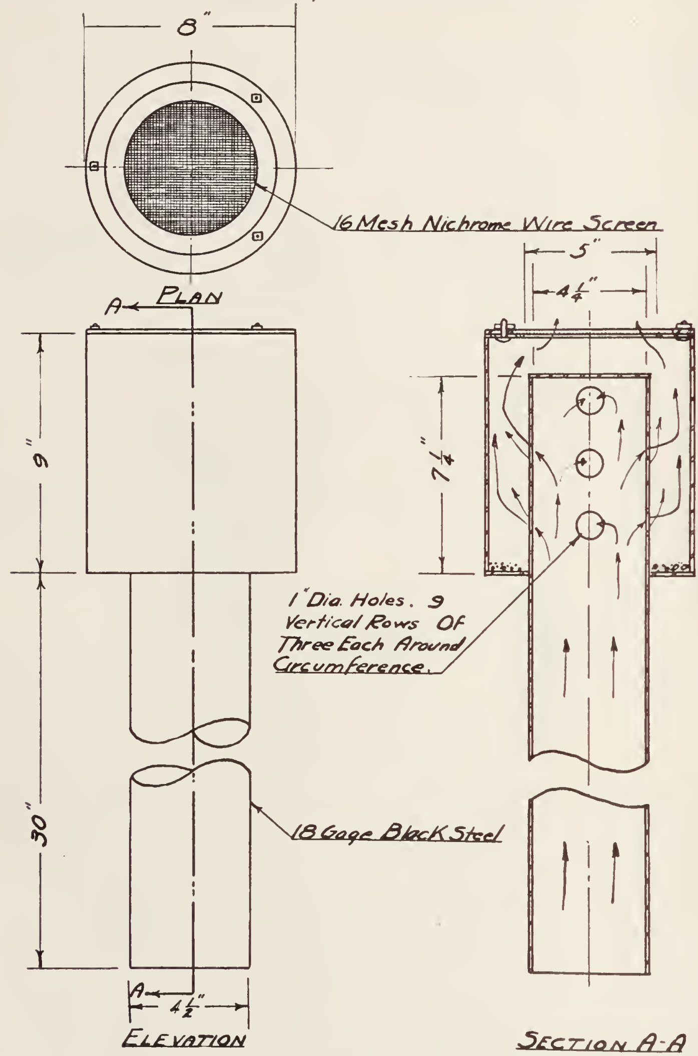

Fig. 19.—Experimental spark arrester.

sizes 2, 3, and 4, respectively (table 11). The back pressure created amounted to 2 inches of water (table 10).

The Case Harvester Arrester.—The Case arrester (fig. 20) consists of a pipe closed off at the upper end and having six vertical rows of ½-inch holes punched near the upper end. The outer shell is 5¼ inches in diam-

eter and 11 inches long, with a closed top and with a 2-inch opening in the bottom for slipping over the end of the inner pipe. Lugs on the pipe 11 inches from the top, and a bolt through the top of the outer shell and

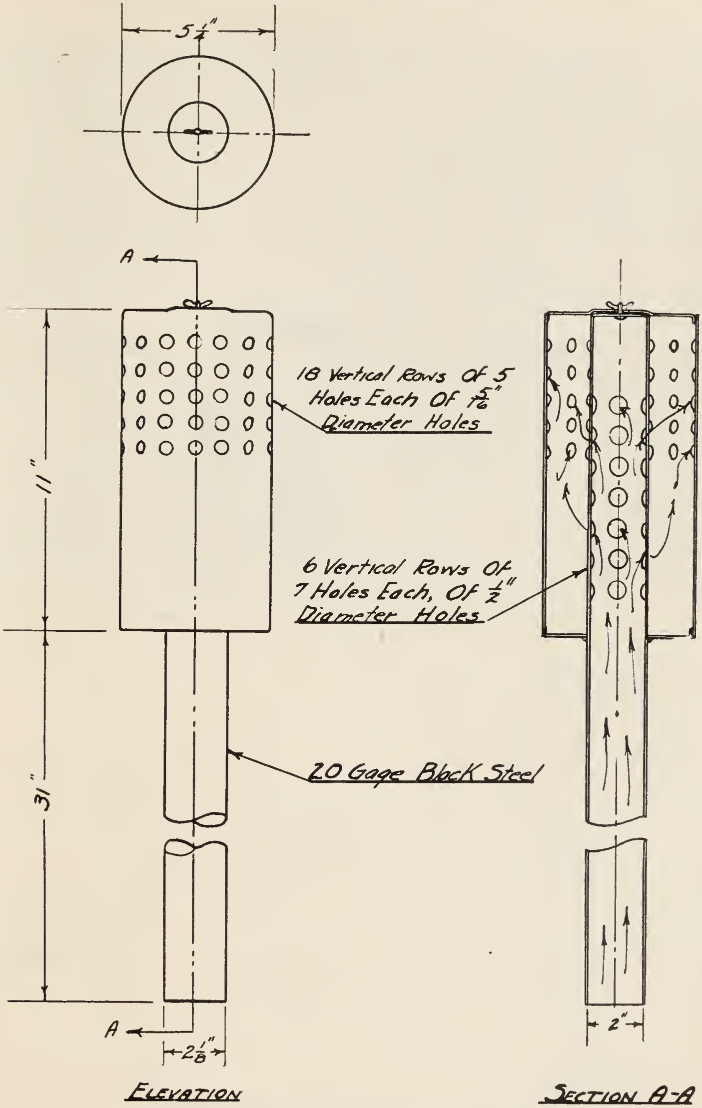

Fig. 20.—Case spark arrester for combines.

the end of the pipe, keep the outer shell concentric to the pipe. A series of eighteen vertical rows of five holes each, $\frac{5}{16}$ inch in diameter, extend through the outer shell. The top holes are 1 inch from the top of the shell and extend down 4 inches.

As some of the holes through the pipe are in line with the holes in the outer shell, obviously carbon can pass directly through the arrester.

The efficiency of the Case arrester was 82.6, 64.6, and 41.4 per cent

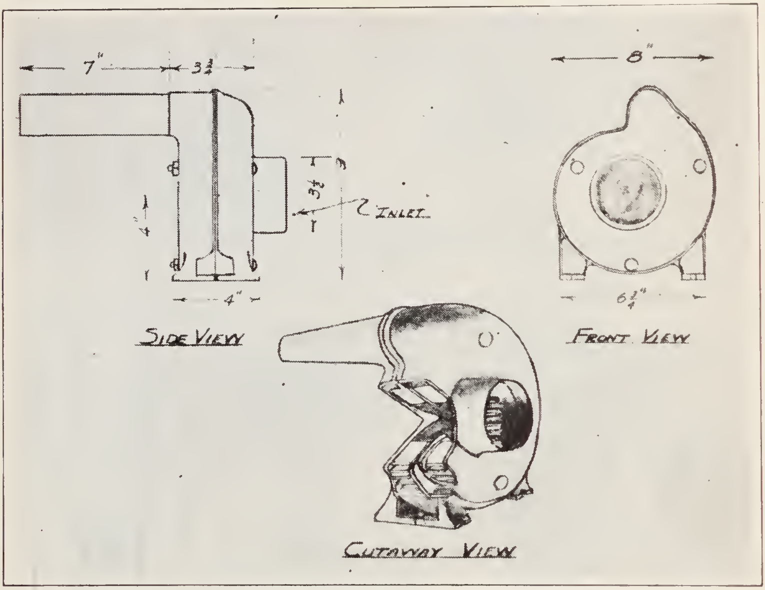

Fig. 21.—Vacuum muffler and spark arrester.

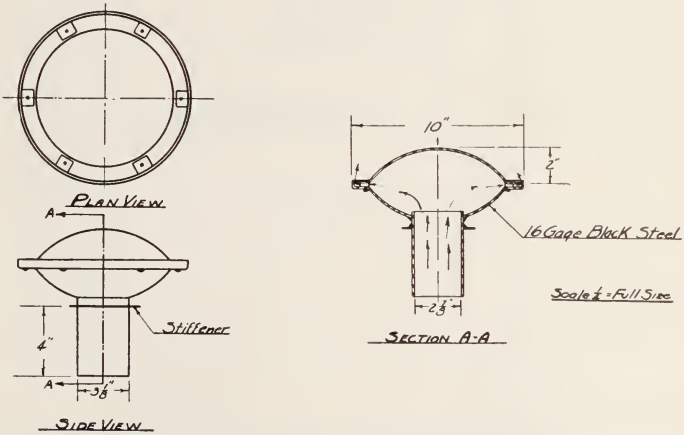

Fig. 22.—Hercules muffler and spark arrester.

for carbon sizes 2, 3, and 4, respectively (table 11). The back pressure amounted to 4.75 inches of water (table 10).

The Vacuum Muffler and Spark Arrester.—The Vacuum device (fig. 21) consists of a somewhat intricate casting. The outer shell, cast in two

parts, is held together by three bolts. The shell is 4 inches wide and 8 inches in diameter, having at the center an inlet 3½ inches in diameter. The outlet is near the outer edge on the opposite side from the inlet.

TABLE 10

Back Pressure Caused by Various Arresters

Name of arrester	Back pressure at beginning of test	Back pressure at end of test
	inches water	*inches water*
Yuba (original)	4.25	4.25
Yuba (modified)	1.75	1.75
Cletrac cyclone	4.75	4.75
Cletrac cyclone (with screens)	5.75	5.75
Experimental	2.0	2.0
McCormick-Deering	10.5	76.07*
Vacuum	5.35	5.35
Funke	2.75	2.75
Case Harvester	4.75	4.75
John Deere	4.25	4.25
Hercules	5.35	15.55†
Caterpillar	12.15	12.15

* Test in which size 2 carbon was used. Back pressure at end of test for size 3 was 48.9 inches water, at end of test for size 4 carbon, 12.6 inches water.

† For size 2 carbon only. Back pressure for sizes 3 and 4 carbons at end of test, same as for beginning.

TABLE 11

Efficiency of Spark Arresters, in Per Cent

Arrester	Carbon size No. 2	Carbon size No. 3	Carbon size No. 4
Yuba	98.0	96.8	69.3
Modified Yuba	99.6	99.3	97.6
Modified Yuba (horizontal)	98.3	97.7	94.4
Modified Yuba (variable load)	99.9	99.6	98.7
Cletrac cyclone	98.7	98.2	79.0
Cletrac cyclone (screened)	100.0	99.9	80.2
Caterpillar	94.0	93.3	77.1
Funke	99.9	96.1	94.3
Funke (variable load)	99.9	99.6	98.2
John Deere	17.6	17.9	11.8
McCormick-Deering	100.0	99.9	18.5
Experimental	100.0	100.0	58.7
Case Harvester	82.6	64.6	41.4
Vacuum	81.7	28.2	15.3
Hercules	83.0	18.5	9.5

Twenty finger-like projections 1½ inches long, cast integral with the side walls, extend toward the middle of the arrester; and two other flat castings with similar fingers are located in the middle. The fingers on the inner walls and on the flat casting dovetail together, leaving a small clearance for the passage of gas and, at the same time, preventing carbon particles from passing until their size is approximately No. 3.

The path of the gas through this arrester is into the center of one side, then through the space between the fingers, and thence to the outlet. There is no place for carbon particles to be retained. If too large to pass the small clearance between the fingers, they remain in the exhaust line until reduced sufficiently to pass through between the fingers.

The efficiency was 81.7, 28.2, and 15.3 per cent for carbon sizes 2, 3, and 4, respectively (table 11). The back pressure amounted to 5.35 inches of water (table 10).

The Hercules Muffler.—This muffler (fig. 22), used occasionally as a spark arrester, consists of two stampings from 16-gauge steel riveted together to form a 4 × 10 inch dome-shaped chamber. A small space between the two halves of the arrester provides passageway for the gas and the smaller carbon particles (including size 3).

The efficiency of this arrester was 83.1, 18.5, and 9.5 per cent for sizes 2, 3, and 4, respectively (table 11). The back pressure amounted to 5.35 inches of water under normal operating conditions, but increased to 15.55 after 100 grams of size 2 carbon particles had been introduced into the exhaust line. On the coarser carbon material the arrester tended to load up, causing greater restriction (table 10).

FIELD TESTS OF ALLOY SCREENS

Common 16-mesh window screen is often placed over the end of exhaust pipes of tractors and trucks to stop the discharge of carbon material. Since iron screens rust and burn out when subjected to the heat from exhaust gases, frequent replacements are necessary. Observations made on one harvester equipped with a screen type of arrester showed three replacements of screen within a week. This screen is liable to burn out without the operator's knowledge, presenting, until replaced, the fire hazard of an unprotected exhaust system. In its use, little attention has been given to proper openings (screen area) to insure that the velocity of exhaust gases, through the screen, will be sufficient to keep the screen relatively free from a carbon coating. For example, the screen type of arrester that was standard equipment on Harris harvesters had a screen area of approximately 113 square inches. As the gas velocity was too low to keep the surface clean, carbon collected on the screen; and later, when the engine was working under a heavy load, the carbon caught fire and was carried away still burning.

An experimental arrester (fig. 19), on which the screen area over the final opening was approximately one-sixth that of the regular Harris arrester, was used to replace the latter. The back pressure on the exhaust system increased only 0.2 of an inch of water in consequence of the

change. At the same time the screen was found to remain free of carbon coating because of the higher velocity of the gases through it.

An attempt was made to find an alloy screen that would withstand the heat and vibration of the exhaust gases. Two such screens, 16 meshes per inch, were selected—namely, "Chromel" and "Nichrome" (trade names for nickel and chromium alloys). Chromel A and Nichrome 4 are identical, containing 80 per cent nickel and 20 per cent chromium. The cheaper grades contain small amounts of iron, which lowers their resistance to heat and vibration, disqualifying them for this type of work. Chromel A or Nichrome 4 withstands these conditions better than other combinations in these series.

An experimental arrester employing Chromel A, 16-mesh screen, having a 46 per cent net opening, showed no signs of failure after 560 hours of use. It was attached to the exhaust pipe of a 30-hp. tractor, only 10 inches from the exhaust manifold, so that the conditions were rather severe.

Failure occurred in 130 to 180 hours of operation when the lower grades of alloy screens, containing iron, were used.

TEMPERATURE EFFECTS FROM COVERING EXHAUST PIPES

A piece of seamless steel tubing, 1¾-inch outside diameter, 8 feet long, was attached to the exhaust manifold of a 22-hp. 4-cylinder engine, 4-inch bore, 4½-inch stroke, operating at 1,170 r.p.m., pulling its rated load. The temperature of the gases in the manifold was 1000°; at the end of the line, 598°. The temperature on the surface of the pipe was 590° at points 2 and 5 feet from the manifold.

The tubing was then wrapped with engineer's tape (asbestos, 7/16 inch thick, 2½ inches wide), and the temperatures were noted at the same points as above. The temperature in the manifold was 985°; at the end of the line, 728°. On the surface it was 320° at 2 feet and 270° at 5 feet from the manifold. Though the coverings materially reduced the surface temperatures, the temperatures of the gases at the end of the line were considerably higher.

The tape was then replaced by a 3-inch galvanized iron pipe, held equidistant from the tubing, giving a clearance of approximately ⅝ inch between the tubing and the pipe. The temperatures of the gases in the manifold and at the end of the line were 975° and 760°, respectively, while the surface temperatures were 200° at 2 feet and 185° at 5 feet from the manifold.

A third pipe 4 inches in diameter was placed around the 3-inch pipe and held equidistant from it. This pipe remained so cool during the test that it did not burn bare hands.

When the 3-inch galvanized pipe was used over the 8-foot length of tubing, in a vertical position, the temperatures along the surface 2 and 5 feet from the manifold were 160° and 140°, respectively, because of natural convection through the space between the two pipes. Since both ends of the 3-inch pipe were open, air circulated freely through it.

EFFECTIVENESS OF MUFFLERS AS SPARK ARRESTERS

A few preliminary tests were run on two mufflers to determine whether or not carbon particles were separated from the exhaust gases. In some cases the carbon was retarded by the muffler; but very little was held permanently. In other words, when carbon was introduced into the line ahead of the muffler, some passed through immediately, the rest at intervals ranging from a few seconds to several minutes.

A test, previously reported, in which a car was treated for carbon removal, revealed that the carbon particles passed through the muffler and tail pipe at temperatures sufficiently high to set cotton batting on fire. The batting was held 18 inches back of the tail pipe. To produce the same results, engine scrapings size 4 had to be heated to a temperature of 1400°.

In general, the average muffler cannot be considered a satisfactory spark arrester. No doubt it assists somewhat, especially in cooling the particles.

SUMMARY

The amount of carbon ejected with the exhaust gas, for the average tractor engine, varies from less than 0.1 gram to 1.0 gram per hour, according to the condition of the engine. On the average, 50 per cent of this carbon is of a size that will not pass a 28-mesh screen. Since the kindling temperature for this carbon varied from 887° for size 5 to 1022° for size 2, evidently carbon can be ignited by the temperatures existing in the exhaust system of an internal-combustion engine.

Fires can be consistently started in dry vegetation, by carbon particles, sizes 1, 2, and 3 (see table 2 for the sizes of carbon samples) with initial temperatures of 1500° to 1600°, during the normal summer conditions in California. In extremely warm dry weather, fires may be started with these sizes at temperatures as low as 1300°.

Fires can be started by size 4 with an initial temperature of 1500°, under conditions favorable to fire.

Carbon size 5, when heated to an initial temperature of 1500°, can start a fire in dry grass on extremely hot dry days. This size of particle, however, lost its heat so rapidly that it ceased to glow within a distance of 9 feet from the furnace, when heated to an initial temperature of

1800°. In practice, therefore, the exhaust pipe could be turned up, discharging into the air, thus providing the necessary distance for cooling the smaller particles before they reach the ground.

The tendency for brush-field and pine-needle litter to be ignited by carbon sparks is about the same. Both catch fire less easily than dry grass. Punk, however, was found not only to be readily ignited but to cause "hang fires"; that is, the material did not blaze immediately, but continued to smoulder and finally burst into flame. In one case the time was 40 minutes.

Exhaust pipes having surface temperatures of 1200° may start fires upon contact with dry grass. Surfaces with temperatures as low as 838° may ignite dry vegetation after several minutes of contact, which could occur if dry grass or straw lodged on an exhaust manifold. If the surface shows even the slightest red color, when viewed at night, it is dangerous and the part should be so placed or guarded that it will not touch vegetation.

Several commercial spark arresters now on the market were above 95 per cent in efficiency in stopping carbon sizes 2 and 3; but all were 80 per cent or below in efficiency for size 4.

One commercial arrester was below 20 per cent in efficiency for all sizes of carbon.

The efficiency of one arrester was increased from 69.3 to 97.6 per cent, for size 4 carbon, by a slight modification in design.

One experimental arrester had an efficiency of 93 per cent or higher for carbon sizes 2, 3, and 4.

The arresters with the highest efficiency created the least back pressure on the exhaust system.

The average muffler cannot be considered a satisfactory spark arrester. No doubt it assists somewhat, especially in the cooling of particles.

Iron screen over the exhaust pipe presents considerable danger, as holes may burn through without the operator's knowledge, thus presenting a fire hazard from an unprotected exhaust system until replaced. Alloy screens consisting of 80 per cent nickel and 20 per cent chromium stood up much better than iron screen. The cheaper grades of these alloy screens, however, contain varying amounts of iron and are, therefore, unsuitable for this type of apparatus.

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